SIGNATURES OF ALFVÉN-CYCLOTRON WAVE-ION SCATTERING: ACE SOLAR WIND OBSERVATIONS

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Abstract

Theory and simulations predict that Alfvén-cyclotron fluctuations in collisionless plasmas scatter ions so as to increase their energies in the directions perpendicular to the background magnetic field. Here linear Vlasov theory in a homogeneous, isotropic plasma of electrons, protons and alpha particles is used to examine the ion cyclotron damping of such fluctuations as a function of the alpha/proton relative speed and the relative alpha particle density. These results imply observable signatures in the perpendicular energies of the alphas. Here extreme values of proton and alpha particle anisotropies measured in the solar wind near 1 AU by the plasma and magnetic field instruments on the ACE spacecraft are reported which are consistent with the signatures expected from Alfvén-cyclotron mode interactions.

1. Introduction

Heavy ions in the solar corona are observed to be much hotter than coronal protons, and to be strongly anisotropic in the sense of $T_{\perp i} >> T_{\parallel i}$ (Here $\perp$ and $\parallel$ denote directions relative to the background magnetic field). *Hollweg and Isenberg* [2002] have provided a thorough review of these observations, and a detailed argument as to why the dissipation of Alfvén-cyclotron fluctuations is likely to be an important contributor to that heating.

The ion heating scenario is as follows: Large-amplitude, low-frequency (that is, well below the proton cyclotron frequency), nonresonant Alfvén waves are generated at the base of, and probably throughout [*Cranmer* 2000, 2001; *Hollweg*, 2000], the corona, as well as in the solar wind [*Roberts et al.*, 1992; *Smith et al.*, 2001]. As these fluctuations propagate upward along open field lines away from the Sun and the coronal plasma becomes collisionless, the decreasing magnetic field leads to wave-particle interactions at cyclotron resonances of ions of successively larger charge-to-mass ratios; this is the "frequency sweeping" scenario. An alternative picture is that magnetic fluctuation energy reaches resonant wavenumbers via a turbulent cascade which may operate even in a homogeneous plasma.

In either case, these resonant interactions lead to ion heating predominately in the directions perpendicular to $\mathbf{B}_o$ [*Marsch et al.*, 1982c; *Tam and Chang*, 1999; *Hollweg*, 2000; *Vocks and Marsch*, 2001]. As the corona expands into the solar wind, the magnetic mirror force accelerates these anisotropic ions to yield the high speeds of the fast solar wind.

Observations of large-amplitude, outward-propagating Alfvén fluctuations throughout the solar wind [*Belcher and Davis*, 1971] suggest that ion heating by Alfvén-cyclotron waves should persist in the interplanetary medium, albeit more weakly than in the corona, and that ion signatures of this process should be evident in measurements from interplanetary spacecraft. Solar wind *in situ* observations near 1 AU show that, particularly in the fast solar wind, the core of the proton velocity distribution often bears a $T_\perp/T_\parallel > 1$ anisotropy [e. g., *Bame et al.*, 1975; *Marsch et al.*, 1982b; *Feldman et al.*, 1996; *Neugebauer et al.*, 2001]. The global adiabatic response of ions flowing outward in the decreasing magnetic field of the solar wind would be to develop the opposite anisotropy, so measurements of $T_{\perp p}/T_{\parallel p} > 1$ have been interpreted as indicators of local scattering by Alfvén-cyclotron fluctuations [e.g., *Marsch et al.*, 2004]. *Marsch and Tu* [2001] and *Tu and Marsch* [2002] showed proton velocity distributions measured from the Helios spacecraft between 0.3 and 0.5 AU that clearly demonstrate the signature of proton pitch-angle scattering by Alfvén-like fluctuations. A major purpose of this manuscript is to describe our search for such signatures in proton and alpha particle observations from the ACE spacecraft in the solar wind near 1 AU.

Models of Alfvén-cyclotron fluctuation heating of heavy ions in coronal and solar wind plasmas may be categorized as analytic-based kinetic theories, fluid model computations, and particle simulations. Models in the first two categories have been reviewed exhaustively by *Hollweg and Isenberg* [2002].

Kinetic analytic models are based on the assumption that the velocity distributions of the scattered ions undergo strong departures from bi-Maxwellian forms. Such models which include both protons and alphas or heavier ions have been developed by *Tam and Chang* [1999]; *Hollweg* [1999, 2000]; *Cranmer* [2001]; *Vocks and Marsch* [2001, 2002]; and *Vocks* [2002]. Calculations using each of these models yields preferential heating of the heavy ions and, more specifically, of the heavy ion perpendicular temperatures as compared to that of the protons. These kinetic models may be relevant to the very low-β plasmas of the solar corona and the solar wind relatively close to the Sun [*Tu and Marsch*, 2002]. However, our interest here is in the intermediate-to-high β plasmas near 1 AU, where ion velocity distributions are observed to be Maxwellian-like and where, we believe, such kinetic models are not appropriate.

Fluid-like models assume that the velocity distributions of the scattered ions remain bi-Maxwellian, so that the ion properties may be represented as velocity moments of such distributions, that is, as densities, flow speeds, and temperatures. Analytically-based fluid models of the corona and/or solar wind which describe both protons and alphas include *Marsch et al.* [1982c]; *Isenberg and Hollweg* [1983]; *McKenzie* [1994]; *Hu and Habbal* [1999]; *Cranmer* [2000]; *Tu and Marsch* [2001a, 2001b]; and *Gary et al.* [2001b].

Most kinetic and fluid models are based on the assumption that, as Alfvén-cyclotron fluctuations propagate to regions of weaker magnetic fields, they encounter cyclotron resonances of successively larger charge-to-mass ratio ions, scattering and heating each species successively. However, these models differ as to how and whether protons may be heated by this process. The coronal models of *Cranmer* [2000, 2001] suggest that heavy ions absorb almost all of the upward-propagating Alfvén wave power, and the model of *Vocks and Marsh* [2001, 2002] and *Vocks* [2002] makes this explicit, yielding very little heating for either the alphas or the protons in the collisionless corona.

Liewer et al. [2001] and *Ofman et al.* [2002] used hybrid simulations to address the interplay between an imposed spectrum of Alfvén-cyclotron fluctuations and ion velocity distributions. In both papers the relative heating is a function of the assumed power spectrum, but for all simulations in which the fluctuations are driven below the helium cyclotron frequency the heavy ions gain substantially more perpendicular temperature than do the protons, in agreement with the analytic models cited above. Furthermore, both the *Liewer et al.* [2001] and the *Ofman et al.* [2002] computations showed that changes in the heavy-ion/proton relative speeds are very small compared to v_A, the Alfvén speed.

The preferential heating of heavy ions by Alfvén-cyclotron fluctuations obtained by each of these three categories of calculations essentially derives from a particular property of these waves. If the heavy-ion/proton relative speed is small compared to v_A, the heavy ions are strongly resonant with Alfvén-cyclotron fluctuations and preferentially absorb their energy, whereas if v_{ip}/v_A for a specific heavy ion species i is positive and becomes sufficiently large, that species becomes nonresonant and the fluctuations preferentially scatter other, resonant ions of larger cyclotron frequencies [*Dusenbery and Hollweg*, 1981; *Isenberg and Hollweg*, 1983; *Gomberoff et al.*, 1996; *Gary et al.*, 2001b]. We use this property in our search for signatures of Alfvén-cyclotron fluctuation scattering of alphas in the solar wind.

Throughout this manuscript we denote electrons with the subscript e, protons by p, and alpha particles (hereafter "alphas") by α. Other symbols used here are defined in the Appendix.

2. Linear Theory

This section describes our use of linear Vlasov theory to determine the parameter regimes of importance for alpha cyclotron damping of Alfvén-cyclotron fluctuations in a homogeneous, collisionless plasma of electrons, protons, and alphas as a minority ion species. Isotropic Maxwellian velocity distributions are assumed for each species. Unless stated otherwise, we use the following dimensionless parameters: $m_p/m_e = 1836$, $m_\alpha/m_p = 4$, $v_A/c = 10^{-4}$, $q_\alpha/q_p = 2$, $\tilde{\beta}_p = 0.10$, $n_\alpha/n_e = 0.02$, $T_p/T_e = 1.0$ and $T_\alpha/T_e = 4.0$. We assume $\mathbf{k} \times \mathbf{B}_o = 0$.

If the alpha component is sufficiently cool and sufficiently dense, its presence splits the ω_r versus $k_\parallel$ dispersion curve of left-hand polarized Alfvén-cyclotron fluctuations into two branches, one at $\omega_r < \Omega_\alpha$ and one at $\Omega_\alpha < \omega_r < \Omega_p$. Several theories of alpha and heavy ion heating by Alfvén-cyclotron fluctuations have been constructed assuming that this is the case; for example, see *Hollweg and Isenberg* [2002]. However, for a sufficiently tenuous, sufficiently hot minor ion species, the dispersion of an Alfvén-cyclotron fluctuation is continuous through the cyclotron frequency of that species. This is illustrated in Figure 1, which shows the real frequency and damping rate as functions of parallel wavenumber for the parameters stated above. For comparison the real frequency and damping rate of the same fluctuation in a plasma with $n_\alpha = 0$ are also illustrated. The differences between the two cases are relatively small; in particular ω_r is a continuous function of $k_\parallel$ through the helium cyclotron frequency.

If $|\zeta_j| > 3$ or $|\zeta_j^\pm| > 3$ for any mode, the resonant $v_\parallel$ lies far from the thermal part of the velocity distribution $f_j(v_\parallel)$ [e. g., *Gary*, 1993]; then that mode is nonresonant and the corresponding wave-particle interactions are weak. If the opposite sense of either inequality holds, it is a necessary but not sufficient condition for resonance and strong damping by the jth species. Figure 1b shows that the magnitudes of both the proton and alpha cyclotron resonance factors for Alfvén-cyclotron fluctuations decrease monotonically with increasing parallel wavenumber. In particular, the onset of damping at $k_\parallel c/\omega_p \simeq 0.30$ takes place near the wavenumber for which the condition $|\zeta_\alpha^-| = 3$ is satisfied, demonstrating that this dissipation is due to the alpha cyclotron resonance. In contrast, the protons remain nonresonant until shorter wavelengths ($k_\parallel c/\omega_p \simeq 0.70$) [e.g., Fig. 3 of *Gary and Borovsky*, 2004], after which their cyclotron resonance dominates the damping. In both the turbulent cascade and frequency sweeping scenarios field fluctuation energy at long wavelengths is the energy source; this figure shows that, as this energy migrates toward larger $k_\parallel c/\omega_p$, it encounters the alpha cyclotron resonance first and heats that species before continuing to the proton cyclotron resonance at still shorter wavelengths.

To gain further insight, we computed damping rates and alpha cyclotron resonant factors for Alfvén-cyclotron fluctuations from linear theory for relevant ranges of several dimensionless parameters. Figure 2 illustrates the damping and alpha cyclotron resonance factor of these fluctuations for four different values of $v_{\alpha p}/v_A$ at $\tilde{\beta}_p = 0.10$. As the alpha/proton relative speed increases from zero, the alpha cyclotron resonance gradually weakens and its contribution to fluctuation damping diminishes until at $v_{\alpha p}/v_A = 0.50$ the damping becomes almost completely due to the proton cyclotron resonance. In contrast, as $v_{\alpha p}/v_A$ becomes negative, the Alfvén-cyclotron mode remains strongly resonant with the alphas and the alpha cyclotron damping becomes stronger, with its onset moving to successively longer wavelengths. Other linear theory calculations at $\tilde{\beta}_p = 0.50$ and at $n_\alpha/n_e = 0.05$ show the same result: as $v_{\alpha p}/v_A$ is increased from zero the alpha cyclotron resonance is weakened and by $v_{\alpha p}/v_A = 0.50$ the damping has reverted to that of an electron-proton plasma of the equivalent β_p.

The second-order theory of *Gary et al.* [2001b] confirmed that an increasing alpha/proton relative speed weakens the alpha cyclotron resonance; if $v_{\alpha p}/v_A$ and the wave amplitudes are sufficiently small, Alfvén-cyclotron waves primarily drive an increasing $T_{\perp\alpha}/T_{\|\alpha}$, but as $v_{\alpha p}/v_A$ increases, the wave energy primarily goes into increasing $T_{\perp p}/T_{\|p}$. *Tu and Marsch* [2001a, 2001b] used this idea to develop a quasilinear theory for oxygen ion and proton heating in the solar corona. In their model, if the Alfvén fluctuation energy density is sufficiently large, the oxygen ions are accelerated, their ability to absorb fluctuation energy is reduced, and the wave energy is able to reach ion resonances at higher frequencies.

The results shown here are based on $\omega_r > 0$, but are valid for both $B_o > 0$ and $B_o < 0$. If we consider Alfvén-cyclotron fluctuations at $\omega_r < 0$, linear theory (not shown here) shows that the alphas become nonresonant when $v_{\alpha p}/v_A$ becomes sufficiently negative, and that alpha cyclotron damping becomes significant only for $|v_{\alpha p}|/v_A << 1$ and all positive values of $v_{\alpha p}$. Thus we summarize the results of Figure 2 as follows: When the alpha/proton relative speed is sufficiently large and in the same direction as the fluctuation phase speed $\omega_r/|k_\||$, the alpha resonance with Alfvén-cyclotron fluctuations is weak, and we expect weak perpendicular heating of the alphas. When $|v_{\alpha p}|/v_A$ is small, whatever its sign, and when $v_{\alpha p}$ is opposite in direction to $\omega_r/|k_\||$, whatever its magnitude, the alpha resonance with such waves is strong, and we expect strong perpendicular heating of the alphas.

Figure 3 shows the damping and alpha cyclotron resonance factor of Alfvén-cyclotron fluctuations for five different values of n_α/n_e at $\tilde{\beta}_p = 0.10$. As long as $n_\alpha/n_e << 1$, the alphas do not make significant changes in $\omega_r(k_\|)$, and ζ_α^- does not change very much as a function of the dimensionless alpha density. Thus Figure 3b shows that the alphas become resonant at sufficiently short wavelengths for all density ratios considered here. However, satisfaction of the resonance condition is not the only factor determining the alpha response to the fluctuations. Figure 3a shows, not surprisingly, that the greater the relative alpha density, the stronger the alpha cyclotron damping. The change in character of the damping rate curve between $n_\alpha/n_e = 0.02$ and 0.05 corresponds to the bifurcation of the ω_r versus $k_\|$ dispersion curve into two branches, one at $\omega_r < \Omega_\alpha$ and one at $\omega_r > \Omega_p$.

Variations of n_α/n_e make no important changes in ζ_α^-, so we need further consideration as to how variations in heavy-ion densities might affect the response of such ions. Conservation of energy demands that, in a homogeneous plasma, the time rate of change of field energy density plus the time rate of plasma species energy density should be zero [*Gary and Tokar*, 1985, Section 4]. For Alfvén-cyclotron fluctuations, $|\delta\mathbf{B}|^2| >> |\delta\mathbf{E}|^2$, so we ignore the contribution of the fluctuating electric field energy density. We consider relatively long wavelengths which are nonresonant with both protons and electrons so that, for $v_{\alpha p} = 0$, it is the alphas which gain most of the energy from the damped fluctuations. Thus

$$\int dk_\parallel \gamma(k_\parallel) \frac{|\delta\mathbf{B}(k_\parallel)|^2}{8\pi} \simeq -\frac{3}{2}\frac{\partial(n_\alpha k_B T_\alpha)}{\partial t} \simeq -\frac{n_\alpha \partial(k_B T_{\perp\alpha})}{\partial t} \tag{1}$$

where the integral is over those wavenumbers at which the alphas are cyclotron resonant but the protons are nonresonant. The right-hand equation in the above expression follows from the assumption that pitch-angle scattering predominantly provides energy to the alphas in the directions perpendicular to $\mathbf{B}_o$. The damping rate γ is no larger in magnitude than the rate at which fluctuation energy is supplied to the alpha cyclotron resonance wavenumber regime whether by turbulent cascade or by frequency sweeping, so it is independent of either n_α or $T_{\perp\alpha}$. Similarly, the magnetic fluctuation energy density in this regime is also independent of the alpha density and temperature, because it is determined through continuity by the longer-wavelength $|\delta\mathbf{B}|^2/8\pi$ of the inertial range which does not depend upon the alpha properties. So it follows that the left hand side of Equation (1) is independent of n_α and the alpha temperatures, and, as a result, the more tenuous the alpha density, the faster the perpendicular heating of the alphas. In terms of dimensionless variables we expect that the largest observed values of $T_{\perp\alpha}/T_{\parallel\alpha}$ should correspond to the smallest measured values of n_α/n_e.

Figure 4 shows the damping and alpha cyclotron resonance factor of Alfvén-cyclotron fluctuations for three different values of T_α/T_p. As the alpha temperature appears in the denominator of the alpha cyclotron resonance factor, an increasing T_α/T_p corresponds to a decreasing $|\zeta_\alpha^-|$, implying that hotter alphas come into cyclotron resonance at smaller values of kc/ω_p, as illustrated in Figure 4b. This is further illustrated in Figure 4a, which suggests that sufficiently hot alphas may produce an observable shift to smaller wavenumbers of the onset of the dissipation range of cyclotron resonant magnetic turbulence.

We have prepared plots in the same format as the three previous figures for variations in β_p and the alpha temperature anisotropy. The results, not shown here, are as we expected: an increase in β_p increases the effective temperature of the alphas, thereby reducing the values of $|\zeta_\alpha^-|$ at long wavelengths and pushing the onset of alpha cyclotron damping to smaller values of kc/ω_p. And a modest increase in $T_{\perp\alpha}/T_{\parallel\alpha}$ makes no important changes in the alpha resonance factor, but reduces the magnitude of the damping rate in the wavenumber regime where the alpha cyclotron resonance is effective, indicating the approach to the helium anisotropy cyclotron instability and a reduction in the ability of the alphas to absorb energy from imposed Alfvén-cyclcotron fluctuations. Of course, the same statements are true for proton cyclotron interaction in an electron-proton plasma [e.g., *Gary and Borovsky*, 2004].

We have carried out similar linear theory calculations for magnetosonic-whistler fluctuations at $\mathbf{k} \times \mathbf{B}_o = 0$ in an electron-proton-alpha plasma. We find, for example, that enhanced alpha cyclotron damping of these fluctuations corresponds to an increasing n_α/n_e (as for the Alfvén-cyclotron mode results of Figure 3) and to an increasingly positive $v_{\alpha p}/v_A$ (in contrast to the Alfvén-cyclotron mode results of Figure 2). However, the most relevant results for this mode concern its dependence on β_p. Although the magnetosonic-whistler mode at $\mathbf{k} \times \mathbf{B}_o = 0$ can become heavily damped at $k_\parallel c/\omega_p \simeq 1$ if $\beta_p \geq 2.5$ [*Stawicki et al.*, 2001], smaller values of β_p correspond to smaller maximum values of $|\gamma|/\Omega_p$. As the substantial majority of ACE observations correspond to $\tilde{\beta}_{\parallel p} \lesssim 1.0$ [e.g., *Gary et al.*, 2001a], ion cyclotron damping of magnetosonic-whistler waves is weak for most ACE observations. So we expect magnetosonic-whistler modes to drive strong proton or alpha $T_\perp/T_\parallel > 1$ anisotropies only infrequently at ACE, and the interpretation of observations developed in the following sections is based on the assumption that ion anisotropy signatures should be driven primarily by Alfvén-cyclotron fluctuations.

3. Some Previous Alpha Observations in the Solar Wind

This section briefly discusses previous solar wind alpha observations which bear on the results presented in subsequent sections. *Aellig et al.* [2001] reported observations from the WIND/SWE experiment which showed that the average value of n_α/n_p rises from a minimum of less than 0.02 around solar minimum to about 0.045 in early 2000. This paper also summarizes previous measurements of solar wind alpha densities.

Papers which report measurements of the alpha/proton relative speed in the solar wind include *Marsch et al.* [1982a], *Neugebauer et al.* [1996], *Steinberg et al.* [1996] and *Reisenfeld et al.* [2001]. As discussed in *Gary et al.* [2003], there is no strong evidence that the alpha/proton relative speed is either driven to a large value by local processes, or that it is constrained by enhanced fluctuations from an electromagnetic alpha/proton instability. Thus, with *Gary et al.* [2003] we assume that the alphas gain a high speed relative to the protons in the corona, and then are gradually decelerated toward the solar wind speed by both collisional and collisionless processes as they stream away from the Sun. Thus, for our discussions of ACE observations near 1 AU, we assume that $|v_{\alpha p}|/v_A$ is relatively fixed and the primary ion response to local wave-particle scattering by Alfvén-cyclotron fluctuations is the development of enhanced kinetic energies in the directions perpendicular to $\mathbf{B}_o$.

Observations of solar wind alphas indicate that their common condition is $T_{\perp\alpha}/T_{\parallel\alpha} < 1$ [*Marsch et al.*, 1982a; *Reisenfeld et al.*, 2001]. Nevertheless, the opposite anisotropy is observed to arise at times [*Neugebauer et al.*, 2001; *Reisenfeld et al.*, 2001; *Gary et al.*, 2002; 2003]. Whatever the source of the $T_{\perp\alpha}/T_{\|\alpha} > 1$ condition, Ulysses observations [*Gary et al.*, 2003] show that this anisotropy is constrained by a β-dependent upper bound derived from the threshold condition of the electromagnetic helium anisotropy instability.

Gary et al. [2002] analyzed proton and alpha anisotropies observed from Ulysses during two intervals, one corresponding to the slow solar wind and one corresponding to the fast wind. Fig. 2 of that paper plots the proton and alpha anisotropies as functions of $v_{\alpha p}/v_A$ and Fig. 3 illustrates the alpha anisotropy as a function of the proton anisotropy for both intervals. The former figure shows that there is no clear trend of the average values of either anisotropy as a function of the alpha/proton relative speed, but that in the slow wind the largest values of both anisotropies are observed at the smallest values of $v_{\alpha p}/v_A$. The latter illustration shows that $T_{\perp\alpha}/T_{\|\alpha}$ and $T_{\perp p}/T_{\|p}$ are correlated in both the slow and fast wind. Here we reconsider this relationship between the proton and alpha anisotropies as observed from ACE.

4. ACE Observations: Fundamentals of the Analysis

Instrumentation on the ACE spacecraft includes the Solar Wind Electron Proton Alpha Monitor (SWEPAM) [*McComas et al.*, 1998a] and the Magnetic Field Experiment (MAG) [*Smith et al.*, 1998]. SWEPAM consists of two fully independent sensors: one for electrons and one for ions. Both instruments are based on spherical section electrostatic analyzers followed by sets of channel electron multiplier detectors. Each can make full three-dimensional measurements of the electron and ion velocity distributions with 64 second time resolution. Here we use the proton and alpha densities as well as parallel and perpendicular proton and alpha temperatures derived from the observed ion distributions.

The parallel and perpendicular temperatures are useful parameters only if the thermal part of the ion velocity distributions are approximately bi-Maxwellian. We have examined proton distributions observed by the SWEPAM instrument using the analysis tool which produced Plate 5 of *Tokar et al.* [2000]. Our analysis of anisotropic distributions sampled from several high speed intervals shows that the beam-like component is typically much more tenuous than the core component. A detailed analysis of this tenuous component is beyond the purview of this manuscript, so we therefore assume that its presence does not strongly violate the bi-Maxwellian condition, and proceed under the assumption that the $T_{\perp p}$ and $T_{\|p}$ derived by integration over the measured distributions are appropriate indicators of proton temperatures.

We used a merged SWEPAM/MAG high resolution data set to carry out a statistical analysis of ion temperature anisotropies measured during several month-long intervals. We extracted from the data several fundamental parameters: the solar wind speed v_{sw}, the solar wind proton density n_p, the parallel and perpendicular temperatures of both the protons and the alphas, the magnitude of the alpha/proton relative speed $|v_{\alpha p}|/v_A$, and

δB_{rms}. To obtain $T_{\perp p}$, $T_{\| p}$, $T_{\perp\alpha}$, and $T_{\|\alpha}$, the second velocity moments of the proton and alpha distributions were computed, diagonalized, and then rotated into a frame with one axis parallel to $\mathbf{B}_o$. After this operation, most observations yielded two perpendicular ion temperatures which are similar; in our figures we include only those points such that the ratio of these two perpendicular temperatures for each species is not larger than 1.3. The δB_{rms} are calculated from MAG data as the RMS vector fluctuation computed every 16 seconds using 3 vector/s measurements.

5. ACE Observations: Correlations

This section describes our search for signatures of Alfvén-cyclotron heating of ions in observations from ACE. Data from four month-long intervals were considered: January 2001, April 2001, May 2002, and December 2002. The first of these encompassed primarily slow solar wind with 300 km/s $\lesssim v_{sw} \lesssim$ 560 km/s, whereas the last three intervals each included two or more high speed streams (e.g., *Smith et al.*, 2004) with 300 km/s $\lesssim v_{sw} <$ 1000 km/s. Because of uncertainties in the measurement of cold electron densities, we here consider $n_p + 2n_\alpha$ to be a proxy for the total electron density n_e.

Theories and simulations of collisionless plasmas yield results which can be expressed either in terms of dimensional or dimensionless variables. Dimensionless variables constitute the more general representation, and are the form which we have used to express our predictions in earlier papers and in Section 2. In contrast, solar wind plasma observations are typically expressed in terms of dimensional parameters; so, to make contact with previous experimental analyses we began with a search for correlations among both dimensional and dimnesionless variables.

First, we considered v_{sw} to be the independent variable. We plotted all the data subject to the constraints stated in Section 4, and did least-squares fits to look for trends of average values. For all four months we found consistent positive correlations between this parameter and δB_{rms}, $T_{\| p}$, $T_{\perp p}$, $T_{\|\alpha}$, and $T_{\perp\alpha}$. In addition we found a consistent negative correlation between the proton density and v_{sw} for all four months. Our search for correlations between dimensionless variables and v_{sw} yielded less consistent results. We found no consistent correlations between the solar wind speed and $T_{\perp p}/T_{\| p}$ or $T_{\perp\alpha}/T_{\|\alpha}$. For three of the intervals (January 2001, May 2002, and December 2002), we found a clear positive correlation between $T_{\|\alpha}/T_{\| p}$ and v_{sw}, in agreement with the 1 AU observations of *Marsch et al.* [1982a]. However, we found no correlation between the alpha-proton temperature ratio and the solar wind speed for the April 2001 data set. Again, for January 2001, May 2002, and December 2002, there is a strong positive correlation between $|v_{\alpha p}|/v_A$ and v_{sw}, in agreement with Fig. 11 of *Marsch et al.* [1982a]. But the April 2001 data set exhibited a weak negative correlation between these two quantities.

Figure 5, using ACE data from April 2001, illustrates some of these results. The most compelling correlations are those between the temperatures and v_{sw} and which are well known; for example, Figure 5c illustrates the correlation between proton temperature and v_{sw} previously demonstrated by *Lopez* [1987].

Second we considered δB_{rms} as the independent variable. Many of the correlations were similar to those discussed in the previous paragraph; for all four months we found consistent positive correlations between the magnetic fluctuations parameter and v_{sw}, $T_{\|p}$, $T_{\perp p}$, $T_{\|\alpha}$, and $T_{\perp\alpha}$. We found no consistent correlations between δB_{rms} and the three dimensionless temperature ratios, but we did find a positive correlation between the solar wind density and δB_{rms}.

These results give no indication that collisionless plasma processes are contributing on average to ion heating in the solar wind near 1 AU. If ion scattering by Alfvén-cyclotron fluctuations were uniformly present throughout the medium, we should uniformly observe protons and alpha heating in the directions perpendicular to $\mathbf{B}_o$, and a correlation of this heating with the amplitude of relatively high-frequency Alfvénic fluctuations. On the other hand, if the episodes of Alfvén-cyclotron heating are sporadic and few in number, they will not make a significant difference to the average values of the plasma parameters. Rather, the signatures of this heating would appear as a few extreme values of ion temperature anisotropies.

Therefore, at this point we changed our approach to look for trends in the extreme values of dimensionless parameters which are likely to indicate variations in the efficacy of the Alfvén-cyclotron interactions. Specifically, the linear theory of Section 2 suggests that perpendicular alpha heating by such fluctuations should be consistently strong when $|v_{\alpha p}|/v_A << 1$, and that perpendicular alpha heating at $|v_{\alpha p}|/v_A \gtrsim 0.5$ should be strong only in the presence of Alfvén-cyclotron fluctuations propagating in the direction opposite to the alpha/proton relative flow. If we make the assumption that alphas usually travel away from the Sun faster than the protons, and if we make the additional assumption that Alfvén-cyclotron fluctuations more frequently propagate away from than toward the Sun, then we expect that the alphas should exhibit signatures of Alfvén-cyclotron heating more frequently when $|v_{\alpha p}|/v_A << 1$ than when $|v_{\alpha p}|/v_A \gtrsim 0.50$.

With this expectation, panels (a) and (b) of Figure 6 show observed temperature anisotropies of protons and alphas as functions of $|v_{\alpha p}|/v_A$ for April 2001. The results, which are similar to plots from the other three months we have considered, are also similar to the Ulysses observations of *Gary et al.* [2002] in that the extreme values of $T_{\perp p}/T_{\|p} > 1$ and $T_{\perp\alpha}/T_{\|\alpha} > 1$ both are observed at relatively small values of $v_{\alpha p}/v_A$. These ACE observations are different from the Ulysses measurements in that the extreme values of $T_{\perp\alpha}/T_{\|\alpha} > 2$ are both more numerous and larger in value than the extreme values of $T_{\perp p}/T_{\|p} > 2$. More specifically, the largest number of extreme alpha anisotropies are observed at $|v_{\alpha p}|/v_A < 0.3$, whereas the greater number of extreme proton anisotropies lie at

$0.2 < |v_{\alpha p}|/v_A < 0.5$, in concert with the theoretical prediction that anti-Sunward propagating Alfvén-cyclotron fluctuations should scatter the alphas more strongly in the former case and resonate with the protons more strongly as $v_{\alpha p}/v_A$ increases. Although we cannot exclude all other possible wave-particle interactions as possible sources of these signatures, we can say that these anisotropies are not due to nonresonant processes such as adiabatic compression, because such processes should heat all particles similarly, independent of their species or relative velocity.

Figure 6c further shows the $T_{\|\alpha}/T_{\|p}$ observed from ACE during April 2001 as a function of $|v_{\alpha p}|/v_A$. The greatest number of extreme values of this dimensionless quantity are observed in the range $0.02 < |v_{\alpha p}|/v_A < 0.05$, suggesting that the parallel heating of the alphas lies in the same parameter range as the maximum perpendicular heating of the protons.

We then reduced the data set to only those observations which satisfied the condition $|v_{\alpha p}|/v_A < 0.2$. The purpose of this was to select those data points most likely to correspond to a strong alpha cyclotron resonance with Alfvén-cyclotron fluctuations.

Figure 7 shows ACE observations of proton and alpha dimensionless temperature ratios as functions of the relative alpha density from April 2001 subject to the constraint $|v_{\alpha p}|/v_A \leq 0.2$. These results are similar to those we obtained from the three other months, and show: (I) The extreme $T_{\perp\alpha}/T_{\|\alpha}$ are larger in value and greater in number than the extreme $T_{\perp p}/T_{\|p}$. (II) The extreme alpha anisotropies are most numerous at $n_\alpha/(n_p+2n_\alpha) \lesssim 0.02$. (III) The extreme $T_{\|\alpha}/T_{\|p}$ are most numerous at $n_\alpha/(n_p+2n_\alpha) \lesssim 0.05$.

When $|v_{\alpha p}|/v_A$ is sufficiently small, Alfvén-cyclotron wave-particle heating favors heating of alphas compared to protons and enhancement of the alpha anisotropy compared to that of the protons. Therefore, all three of these results are consistent with this process. We cannot claim that these signatures are unique to Alfvén-cyclotron heating, because other wave-particle interactions may provide similar signatures on the ion anisotropies. However, we do exclude cyclotron damping by magnetosonic-whistler fluctuations as the source of these signatures, because our results reported in Section 2 indicate that such waves should drive alpha anisotropies only at relatively large and positive values of $v_{\alpha p}/v_A$, and at relatively large values of β_p which do not correspond to most of the data values considered here. To the extent that the Landau resonance provides heating parallel to $\mathbf{B}_o$, we can exclude fluctuations with this interaction as being the source of these signatures, although the consequences of the Landau resonance at high β have not yet been simulated for either the Alfvén-cyclotron or the magnetosonic-whistler modes.

Figure 8 shows the same categories of ACE observations from April 2001, but this time subject to the constraint $0.50 < |v_{\alpha p}|/v_A$. These results are similar to those we obtained from the three other months, and show: (I) The extreme $T_{\perp\alpha}/T_{\|\alpha}$ are larger in value and much greater in number than the extreme $T_{\perp p}/T_{\parallel p}$. (II) The extreme alpha anisotropies are most numerous at $n_\alpha/(n_p + 2n_\alpha) \lesssim 0.01$. (III) The extreme $T_{\parallel\alpha}/T_{\parallel p}$ are most numerous at $n_\alpha/(n_p + 2n_\alpha) \lesssim 0.05$. The theory of Section 2 indicates that a possible source of the extreme $T_{\perp\alpha}/T_{\parallel\alpha} > 1$ anisotropies of Figure 8b and of Figure 6b at $|v_{\alpha p}|/v_A \geq 0.50$ is scattering by Alfvén-cyclotron fluctuations propagating antiparallel to the alpha/proton relative velocity. However, we cannot discern the direction of wave propagation from the available data, so we cannot determine whether these observations represent a confirmation of that theory.

6. Conclusions

The solar corona is observed only by remote sensing, so that information about plasma conditions near the Sun is limited. In contrast there are many spacecraft which make *in situ* measurements of the solar wind, providing a rich source of information about plasma and magnetic field conditions in that medium, especially near 1 AU.

Although the energy densities of particles and fields in the corona are many orders of magnitude greater than those in the solar wind near Earth, the two regions are directly connected. So many of the basic plasma processes which act in the corona also act in the solar wind; by studying the signatures of fundamental plasma processes in the solar wind we can gain insight into how these same processes act in the corona.

We have presented theoretical arguments that, in any sufficiently homogeneous, sufficiently collisionless electron-proton-alpha plasma, Alfvén-cyclotron fluctuations at $\mathbf{k} \times \mathbf{B}_o = 0$ and at appropriate wavelengths preferentially heat alphas in the directions perpendicular to $\mathbf{B}_o$ if $0 \leq |v_{\alpha p}| << v_A$ and $n_\alpha/n_e << 1$. We have furthermore presented ACE observations consistent with these predictions, such that $T_{\perp\alpha}/T_{\parallel\alpha}$ has its most extreme values when $|v_{\alpha p}|/v_A \lesssim 0.3$, as in Figure 6b, and when $n_\alpha/n_e \lesssim 0.02$, as in Figure 7b. The extreme alpha anisotropies of Figure 8b are consistent with linear theory of Alfvén-cyclotron mode interactions only if the fluctuations and the alphas propagate in opposite directions relative to the protons. Further research will be necessary to provide a more conclusive interpretation of the results of Figure 8.

The linear theory arguments of Section 2 are qualitative and can certainly be improved through the use of hybrid computer simulations such as those of *Liewer et al.* [2001]. More generally, it would be useful to use full particle-in-cell simulations of Alfvén-cyclotron fluctuation interactions with both protons and alphas to quantify not only the signatures of the ion cyclotron resonances at $\mathbf{k} \times \mathbf{B}_o = 0$, but also the signatures due to the ion Landau resonances which arise at sufficiently large β and sufficiently oblique angles of propagation [*Gary and Borovsky*, 2004].

We believe that the observations reported here represent the first evidence for Alfvén-cyclotron wave-ion interactions in the solar wind near 1 AU. The signatures we have described are sporadic, indicating that these interactions arise infrequently. Nevertheless, we believe that the detailed character of *in situ* plasma and magnetic field observations can provide a useful basis for testing various theories of wave-particle interactions, and that the resulting improvements in those theories will yield a more accurate and quantitative application of those theories to the solar corona where, presumably, these interactions are much stronger and more consistent.

Appendix: Definitions

We use subscripts $\|$ and $\perp$ to denote directions relative to the background magnetic field $\mathbf{B}_o$. The species subscripts are p for protons, α for doubly ionized helium ions, and e for electrons. For the jth species we define $\beta_{\|j} \equiv 8\pi n_j k_B T_{\|j}/B_o^2$; $\tilde{\beta}_{\|j} \equiv 8\pi n_e k_B T_{\|j}/B_o^2 = (n_e/n_j)\beta_{\|j}$; the plasma frequency based on the total electron density, $\omega_j \equiv \sqrt{4\pi n_e e_j^2/m_j}$; the cyclotron frequency, $\Omega_j \equiv e_j B_o/m_j c$; the thermal speed, $v_j \equiv \sqrt{k_B T_{\|j}/m_j}$; and the average flow velocity $\mathbf{v}_{oj}$. We define the Alfvén speed as $v_A \equiv B_o/\sqrt{4\pi n_e m_p}$, and the alpha/proton relative flow velocity as $\mathbf{v}_{\alpha p} \equiv \mathbf{v}_{o\alpha} - \mathbf{v}_{op}$. The complex frequency is $\omega = \omega_r + i\gamma$, the Landau resonance factor of the jth species is $\zeta_j \equiv \omega/\sqrt{2}|k_\||v_j$, and the cyclotron resonance factors of the jth species are $\zeta_j^{\pm} \equiv (\omega \pm \Omega_j)/\sqrt{2}|k_\||v_j$. We define θ as the angle between $\mathbf{k}$ and $\mathbf{B}_o$, so that $\hat{\mathbf{k}} \cdot \hat{\mathbf{B}}_o = \cos(\theta)$.

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Figure Captions

Figure 1. Linear theory results at $\mathbf{k} \times \mathbf{B}_o = 0$: (a) The real part of the frequency and damping rate and (b) the proton and alpha cyclotron resonance factors of Alfvén-cyclotron fluctuations as functions of the parallel wavenumber. The solid lines represent fluctuations in an electron-proton plasma with $\beta_p = 0.10$. The dashed lines and line of open circles represent fluctuations in an electron-proton-alpha plasma with $\tilde{\beta}_p = 0.10$, $n_\alpha/n_e = 0.02$, $T_p/T_e = 1.0$, and $T_\alpha/T_e = 4.0$. All species are isotropic and $v_{\alpha p} = 0$.

Figure 2. Linear theory results at $\mathbf{k} \times \mathbf{B}_o = 0$: The (a) damping rates and (b) alpha

resonance factors of Alfvén-cyclotron fluctuations in a homogeneous, collisionless electron-proton-alpha plasma as functions of the parallel wavenumber. The four curves of individual symbols correspond to successively increasing values of the alpha/proton relative speed; from left to right $v_{\alpha p}/v_A = 0$, 0.10, 0.20 and 0.50. The solid curve represents results for an electron-proton plasma with $n_\alpha = 0$. Other parameters are the same as stated in the caption of Figure 1.

Figure 3. Linear theory results at $\mathbf{k} \times \mathbf{B}_o = 0$: The (a) damping rates and (b) alpha resonance factors of Alfvén-cyclotron fluctuations in a homogeneous, collisionless electron-proton-alpha plasma as functions of the parallel wavenumber. The curves correspond to different values of the dimensionless alpha density; in (a) from right to left $n_\alpha/n_e = 0$, 0.01, 0.02, 0.10, and 0.05. Other parameters are the same as stated in the caption of Figure 1.

Figure 4. Linear theory results at $\mathbf{k} \times \mathbf{B}_o = 0$: The (a) damping rates and (b) alpha resonance factors of Alfvén-cyclotron fluctuations in a homogeneous, collisionless electron-proton-alpha plasma as functions of the parallel wavenumber. The curves of individual symbols correspond to $T_\alpha/T_p = 1$, 4, and 8 as labeled. The solid curve represents results for an electron-proton plasma with $n_\alpha = 0$. Other parameters are the same as stated in the caption of Figure 1.

Figure 5. ACE observations: six quantities observed during April 2001 as functions of v_{sw}. The data has been reduced as described in the text. (a) The proton density, (b) the magnetic fluctuation amplitude, (c) the parallel proton temperature, (d) the parallel alpha temperature, (e) $T_{\perp p}/T_{\| p}$, and (f) $T_{\perp \alpha}/T_{\| \alpha}$.

Figure 6. ACE observations: three quantities observed during April 2001 as functions of $|v_{\alpha p}|/v_A$. The data has been reduced as described in the text. (a) $T_{\perp p}/T_{\| p}$, (b) $T_{\perp \alpha}/T_{\| \alpha}$, and (c) $T_{\| \alpha}/T_{\| p}$.

Figure 7. ACE observations: three quantities observed during April 2001 as functions of $n_\alpha/(n_p + 2n_\alpha)$. The data has been reduced as described in the text, with the further condition that only data points corresponding to $|v_{\alpha p}|/v_A \leq 0.2$ have been included. (a) $T_{\perp p}/T_{\| p}$, (b) $T_{\perp \alpha}/T_{\| \alpha}$, and (c) $T_{\| \alpha}/T_{\| p}$.

Figure 8. ACE observations: three quantities observed during April 2001 as functions of $n_\alpha/(n_p + 2n_\alpha)$. The data has been reduced as described in the text, with the further condition that only data points corresponding to $0.50 \leq |v_{\alpha p}|/v_A$ have been included. (a) $T_{\perp p}/T_{\| p}$, (b) $T_{\perp \alpha}/T_{\| \alpha}$, and (c) $T_{\| \alpha}/T_{\| p}$.